Effect of testosterone administration and weight training on muscle architecture

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ABSTRACT

BLAZEVICH, A. J., and A. GIORGI. Effect of testosterone administration and weight training on muscle architecture. Med. Sci. Sports Exerc., Vol. 33, No. 10, 2001, pp. 1688–1693. Purpose: The purpose of this study was to assess muscle architecture changes in subjects who were administered supraphysiologic doses of testosterone enanthate (TE) and concurrently performed heavy resistance training. Methods: Ten subjects were randomly selected from the 21 subjects who participated in a previously published study (12). Subjects were allocated to one of two groups as per Giorgi et al. (12) and received either a saline-based placebo (nonTE) or a 3.5-mg·kg\(^{-1}\) body weight dose of TE by deep intramuscular injection once a week for 12 wk. Subjects also performed heavy resistance training using exercises that targeted the triceps brachii muscle. Before and after the training period, free-weight one-repetition-maximum (1-RM) bench press strength was tested, muscle thickness and pennation of the triceps brachii lateralis were measured using ultrasound imaging, and fascicle length was estimated from ultrasound photographs. Results: There were no significant between-group differences in muscle thickness changes despite a trend toward increased thickness in TE subjects (TE, 23.5%, vs nonTE, 13.8%). However, 1-RM bench press performance and muscle pennation increased significantly in TE subjects compared with nonTE subjects (\(P < 0.05\)). There was also a trend toward longer fascicle lengths in the muscles of nonTE subjects. Conclusion: The results of the present study suggest that the use of TE in conjunction with heavy resistance training is associated with muscle architecture changes that are commonly associated with high-force production. Since there was little difference between the groups in muscle thickness, changes in pennation and possibly fascicle length may have contributed to strength gains seen in TE subjects. Key Words: STEROID, PENNATION, ULTRASOUND, TRICEPS BRACHII, FASCICLE LENGTH

The main effect of exogenous testosterone and its derivatives on the musculoskeletal system is to increase muscle mass and strength. Numerous studies have reported increases in body weight (3,9,10,23) and lean body mass (7,8,23) with the use of anabolic steroids. Some research has also shown that steroid use, when combined with resistance training, is associated with increases in muscle fiber area (22) and muscle cross-sectional area (3). These increases in muscle mass are primarily linked to the reduced effects of catabolic glucocorticosteroids that are released during stress (15) and an increased rate of protein synthesis (14).

Increases in isometric strength (1,2,17), isokinetic strength (10), and muscle power (2,32) have been documented after steroid administration. Low steroid doses (<150 mg total testosterone), suboptimum training loads, and disparity between training and testing modes have often compromised studies that found no performance effects of steroid use when accompanied by resistance training (5,6,13,18,25) (for review, see Haupt and Rovere (15)). As such, steroids are commonly believed to improve human physical performance by increasing muscle size and strength.

Although research has examined changes in muscle size with steroid use, no research has investigated muscle architecture changes. A muscle’s architecture has been reported to influence its contraction properties (4,28). Generally, muscles that are recruited during high-force, low-velocity contractions have large pennation and/or short fibers (4,19,20,29), whereas muscles recruited during low-force, high-velocity movements typically have smaller pennation and longer fibers (4,24). Indeed, Kawakami et al. (20) reported increases in muscle pennation accompanying muscle size increases after resistance training in five subjects. Therefore, one would expect weight trainers who often perform high-force, low-velocity contractions to possess muscles of larger pennation and shorter fiber lengths. Given that those subjects who are administered supraphysiologic doses of steroids typically gain muscle mass and strength faster, one might also expect their architectural changes to be more pronounced.

In 1999, Giorgi et al. (12) published data showing significantly greater gains in muscle size and strength in subjects who were administered a 3.5-mg·kg\(^{-1}\) body weight dose of testosterone enanthate (TE) than a control group during a 12-wk resistance training period. It is possible that architectural changes could have contributed to the greater strength changes in TE subjects. If this was the case, a clear difference in architectural adaptations would be seen...
between subjects who were and were not administered TE. During the study, ultrasound photographs of the triceps brachii muscle were taken for 10 subjects (see Methods) from which muscle pennation and fascicle length (used as an indicator of fiber length) could be measured. The purpose of the present study, therefore, was to compare muscle architecture changes between subjects who were administered supraphysiologic doses of TE and concurrently performed heavy resistance training with those who performed resistance training but were not administered TE. Some of the data for subjects in the present study have been previously published (12).

METHODS

Subjects. Of the 21 subjects who volunteered for the original study (see Giorgi et al. (12)), architectural changes were investigated in 10 of the male subjects (mean ± SD: age, 22.4 ± 3.8 yr; height, 178.7 ± 6.5 cm; weight, 84.1 ± 8.1 kg). One subject (TE group) chosen for analysis did not complete the 12 wk; his data were not included in the analysis. The low subject number reflected time and funding constraints. Written informed consent was obtained from subjects before their participation. All subjects were currently weight training at least three times a week before taking part in the study and had at least 1 yr of weight training experience. Thus, none of the subjects could be regarded as novice weight trainers. Each subject produced a urine sample to be assayed for the presence of anabolic steroids and other substances banned by the International Olympic Committee (IOC). None of the subjects were taking performance-enhancing substances before the study. The study was approved by the Human Experimentation Ethics Committee of Southern Cross University, Australia. Approval for a clinical trial of TE was granted by the Therapeutic Goods Administration (Australia), and the New South Wales Department of Health, Australia, granted approval for TE purchase.

Drug screening procedure. A screening (urinalysis) for drugs prohibited by the IOC was performed before participation in the study. No subjects were taking IOC-banned substances. Urine was also obtained after 6 and 12 wk to monitor testosterone levels. All subjects refrained from the ingestion of alcohol or caffeine for 24 h before sampling (21). Subjects also emptied their bladder 1 h before producing a urine sample to ensure a clean and useable sample. Urine collection took place at the same time of day (4–6 p.m.) to control for effects of circadian variations (11,21). The screening was performed at the IOC-accredited Australian Sports Drug testing Laboratories (Pymble, Sydney, Australia).

Protocol. Photographs of the subjects’ triceps brachii lateralis muscles were taken using ultrasound imaging. From an on-screen image and the photographs, muscle thickness, pennation, and fascicle length were determined. These measures have been previously performed on the triceps muscle (19). Subsequently, subjects performed a free-weight one-repetition-maximum (1-RM) bench press test (see Giorgi et al. (12)) to assess the strength of their chest and arm musculature. 1-RM was typically reached by the fourth maximal attempt. During the training period, five subjects were randomly assigned to receive injections of TE (TE group), whereas the remaining four subjects were injected with a placebo (non-TE group). Muscle thickness, pennation, fascicle length, and 1-RM bench press measures were then repeated to allow assessment of strength and muscle architecture changes.

Muscle thickness and pennation measurement. Muscle thickness and pennation of the triceps brachii lateralis was determined at a point midway between the tip of the acromion process of the scapula and the olecranon process of the ulna. This distance was measured using a set of Holtain anthropometric calipers (Harpenden type, Holtain Ltd., Crymmych, Pembrookshire, United Kingdom). Care was taken that precise lengths were measured and the reliability of these measurements was determined before the investigation taking place (see Giorgi et al. (12)). Results of repeated measurements on the triceps muscle have been previously published (20), and the reliability of the sonographer has also been previously reported (27). Subjects stood with the elbow flexed to 90° and the forearm resting on a bench. The upper arm was positioned vertically by the subject’s side. After applying hypoallergenic, water-soluble transmission gel to the skin, an Acuson 8 L5 (8 MHz linear; Mountain View, CA) ultrasound transducer was placed on the surface of the posterior arm. The muscle thickness was determined by the Acuson Sequoia 512 system after the muscle was manually traced on the image screen. Three trials were recorded for the muscle thickness measurements, with the mean score being used for subsequent analysis. The subjects had remained relaxed and did no strenuous activity before testing.

Photographs of the muscle were taken immediately after measurement of muscle thickness by rotating the scanning head to obtain a longitudinal image (19,20). Lines were drawn along the aponeurosis and echoes from interspaces among the fascicles on the photograph (Fig. 1) and the angles made by these lines measured by goniometer to the nearest 0.5°. Pennation of the muscle was taken as the median three repeated angle measurements.

Estimation of fascicle length. Fascicle length (FL) was estimated as the length of the hypotenuse of a triangle with an angle equal to the pennation angle (θ) and the side opposite to this angle equal to the muscle thickness (T), where FL = (T/sinθ). Thus, fascicles were assumed straight and the model did not account for fascicle curvature. Fascicle length has been commonly estimated by this method (16,20,24). An error of approximately 3% can be expected for relaxed muscles with short fascicles when fiber curvature is not accounted for (unpublished observations).

Training program. The training program used by the subjects has been described previously (12). Briefly, subjects performed a weight training regimen for 12 wk. Training involved four weight training sessions per week with two sessions consisting of exercises that targeted the triceps; the other two sessions consisted of exercises targeting other

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body parts. All subjects were encouraged to stretch after training, although this was not controlled in the study. Training was periodized to prevent staleness and its intensity consistently increased to provide a stimulus for muscle growth. Training logs were kept for each subject to ensure adherence to the program.

**Testosterone administration procedure.** The testosterone administration and subject group allocation procedures have been described previously (12). Briefly, subjects received either saline-based placebo (nonTE) or a 3.5-mg·kg⁻¹ body weight dose of TE (Primoteston Depot, 250 mg). The dose is equivalent to that used in studies assessing the efficacy of TE as a male contraceptive (33) but exceeds those purported to be used by power athletes such as sprint runners (34). The administration of TE and the placebo was performed weekly by deep intramuscular injections into the outer, upper quadrant of the gluteus maximus muscle using a 21-gauge (1 3/4 inch) needle. The outer, upper quadrant was targeted to minimize the risk of impinging on nerves or blood vessels. A qualified nurse performed all injections at the same time each week for each subject for the 12 wk of training. Testosterone (urinary) levels were significantly increased after TE administration in TE subjects (Fig. 2) (P < 0.01).

**Data analysis.** The validity of ultrasound measurement as a means of measuring architecture of the triceps muscle has been shown elsewhere (19), and the reliability of the sonographer has been presented previously (27). Reliability of muscle pennation measures was shown here by calculating the average difference between the first two of three measurements on all subjects. The average difference was expressed as positive) between the first two pennation angle measures of all fiber bundles was 0.2°. The average absolute difference (i.e., all differences except those purported to be used by power athletes such as sprint runners (34). The administration of TE and the placebo was performed weekly by deep intramuscular injections into the outer, upper quadrant of the gluteus maximus muscle using a 21-gauge (1 3/4 inch) needle. The outer, upper quadrant was targeted to minimize the risk of impinging on nerves or blood vessels. A qualified nurse performed all injections at the same time each week for each subject for the 12 wk of training. Testosterone (urinary) levels were significantly increased after TE administration in TE subjects (Fig. 2) (P < 0.01).

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**RESULTS**

**Reliability of pennation and thickness measures.**

The average absolute difference (i.e., all differences expressed as positive) between the first two pennation angle measurements of all fiber bundles was 0.2°. The average pennation angle was 9.8°; therefore, an average difference of 0.2° represents a magnitude of only 2% of the average pennation angle. Therefore, there was little difference between repeated measurements. Estimates of triceps thickness were also reliable (triceps brachii lateralis thickness: TEM% = 0.4%, ICC = 0.95).

**Changes in strength and muscle architecture.**

Pre- and posttraining data for bench press strength and muscle architecture measures are presented in Table 1. There was a significant time × group interaction for bench press performance such that after the 12 wk of training, the increase in bench press performance by TE was greater than nonTE (F[1,7] = 17.6, P < 0.05).

The result was similar for muscle pennation, which increased more in TE than in nonTE subjects (time × group interaction, F[1,7] = 10.24, P < 0.02). Indeed 60% of the variance in muscle pennation can be attributed to the time by group interaction (E² = 0.59), suggesting that...
TABLE 1. Mean (SD) pre- and posttraining values for bench press strength, muscle pennation, and thickness.\textsuperscript{a}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Group} & \textbf{Before} & \textbf{After} & \textbf{Before} & \textbf{After} & \textbf{Before} & \textbf{After} \\
\hline
TE & 93.3 (16.6) & 108.1 (16.1)\textsuperscript{a} & 8.1 (2.3) & 11.3 (3.4)\textsuperscript{b} & 24.6 (6.3) & 31.8 (4.8)\textsuperscript{c} \\
NonTE & 109.8 (20.0) & 113.7 (24.9) & 12.0 (1.8) & 11.5 (1.9) & 28.0 (7.2) & 31.8 (6.8)\textsuperscript{c} \\
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\end{tabular}
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\textsuperscript{a}TE subjects were administered testosterone enanthate; NonTE, subjects were not administered testosterone enanthate.
\textsuperscript{b}TE subjects increased significantly more in bench press performance and muscle pennation than nonTE subjects ($P < 0.05$). There was a general increase in muscle thickness that was not different between the groups.
\textsuperscript{c}Change was significantly greater for TE subjects.
\textsuperscript{d}Significant change over time, but no difference between groups.
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TE administration was associated with increased pennation. Low pennation of the muscle compared with previously published data (19) can be attributed to the long length at which the muscle was tested; the elbow was flexed to 90°, with the upper arm positioned vertically by the subject’s side.

For muscle thickness, there was an effect of time ($F[1,7] = 34.0, P < 0.01$), but no interaction effect ($F[1,7] = 3.2, P = 0.18$). Therefore, there was an increase in triceps muscle thickness after 12 wk of training, but the increase was not influenced by TE administration (no group effect). This was despite the mean increase being slightly greater for TE subjects (effect size = 0.54; 29.5% increase in the TE group, 13.8% increase in the nonTE group).

There was a nonsignificant time $\times$ group interaction for fascicle length change ($F[1,7] = 3.9, P < 0.1$), with TE subjects decreasing (mean score, 17.9 cm to 16.6 cm) and nonTE subjects increasing (mean score, 13.3 cm to 16.0 cm) in fascicle length. Low reliability of the estimation method and low subject numbers may have prevented significant findings.

DISCUSSION

The purpose of this study was to assess muscle architecture changes in subjects who were administered supraphysiologic doses of a steroid and concurrently performed heavy resistance training. Subjects who were administered TE did not significantly increase their triceps muscle thickness more than nonTE subjects. This was despite the mean increase in thickness being greater for TE subjects (29.5% vs 13.8%) and a significant increase in urinary testosterone of TE subjects (Fig. 2) ($P < 0.01$). The lack of statistical difference between the groups may be a result of low subject numbers reducing statistical power (power = 0.34). However, the moderate effect size (ES = 0.54) suggests that there indeed may not have been a distinct difference between the group’s change in triceps muscle size. Furthermore, no significant differences were reported in the data from 21 subjects by Giorgi et al. (12). In that publication, triceps thickness increased in TE subjects from 25.5 $\pm$ 5.8 mm to 33.5 $\pm$ 4.0 mm, and in nonTE subjects from 25.7 $\pm$ 6.7 mm to 31.3 $\pm$ 6.3 mm. These changes are similar to those reported in Table 1 of the present study. As such, the muscle thickness data of the subjects in the present study are similar to those of the whole 21 subjects presented by Giorgi et al. (12).

Given the relationship between pennation ($\theta$), fascicle length (FL), and muscle thickness (T) such that $T = FL\sin\theta$, significant increases in muscle thickness can result not only from muscle hypertrophy but from either or both increases in pennation and fascicle length (e.g., small changes in fascicle length and pennation could be reflected in significant changes in thickness). TE subjects showed greater increases in pennation, whereas nonTE subjects showed longer fascicle lengths after training. These changes would likely result in similar increases in muscle thickness. The result contradicts findings of Bhasin et al. (3), who showed a significant difference in triceps muscle size between “steroid” and “control” groups as measured by magnetic resonance imaging (MRI) after 10 wk of training. However, the larger amount of steroid given to subjects in that study (600 mg·kg$^{-1}$) may have contributed significantly to their increased muscle thickness.

Despite no significant difference in triceps muscle size between TE and nonTE groups in the present study, the TE group showed greater improvement in their 1-RM bench press (Table 1). The greater strength increases in TE subjects were also reported in the whole 21 subjects (12). In that publication, 1-RM bench press strength of TE subjects improved from 98 $\pm$ 19 kg to 119 $\pm$ 19 kg and in nonTE subjects from 100 $\pm$ 16 kg to 109 $\pm$ 18 kg. Again, the changes in bench press strength were similar to those in the present study, although perhaps the bench press strength of nonTE subjects used for this analysis was slightly higher than the average of the whole 21 subjects. Nonetheless, strength changes mirrored those of the 21 subjects as a whole (12). It is possible then that since muscle thickness and strength changes were similar to those presented by Giorgi et al. (12), the architectural changes shown here might also be indicative of those that would have occurred in the larger groups of 21 subjects, although this cannot be confirmed.

Subjects who were administered TE showed greater increases in pennation compared with the nonTE controls. In fact, there was no change in triceps pennation for nonTE subjects after 12 wk of resistance training. Larger pennation has been seen in muscles that commonly produce high-force contractions (4,30) and could theoretically aid strength development by allowing more...
contractile tissue to attach to a given area of tendon (19,20,28). Tendon excursion is also greater for a given length of fiber shortening when the angle between the fascicles and tendon is greater (26). This is because fibers in pennate muscles not only shorten but also rotate during muscle shortening (Fig. 3). Effectively, both the length and velocity of fiber shortening would be less in muscles of greater pennation. The fibers would therefore be able to produce greater force according to their length-tension and force-velocity properties. As such, the increases in pennation seen in TE subjects may theoretically have had a positive influence on their strength development.

Fascicle length has also been linked to muscle contraction properties such that muscles with longer fibers are recruited during high-velocity contractions (4,24). Muscles that consistently produce high-velocity contractions may adapt to longer fiber lengths because longer fibers possess higher shortening velocities (29,31). In humans, muscles that provide high-force contractions often contain shorter fibers (30). For subjects in the present study, there was a trend toward longer fascicles in the triceps brachii lateralis of nonTE subjects (13.3 cm to 16.0 cm), whereas there was a small decrease or no change in TE subjects after training. In our opinion, the long fascicle length estimates can be attributed to the low pennation and nonparallel relationship between the line of the aponeurosis and the muscle border at which the fascicles terminate. Our ultrasound images showed that the fascicles terminate near the muscle’s origin after traversing approximately 10–12 cm. Although fascicle length determined in the present study can only be considered an estimate (given the error in fascicle length prediction and small sample size used for the analysis), the result provides further evidence of specific adaptations such that the muscles of TE subjects became better adapted for high-force contractions than nonTE subjects. Consequently, subjects who use testosterone derivatives in supraphysiologic doses while performing high-intensity resistance training may attain muscle architecture better suited to high-force development compared with those who do not.

The mechanism by which TE affected architectural changes is unclear. Some authors have suggested that larger muscles possess greater pennation (19,20) because more muscle mass could then attach to the tendon (19,20,28). Given that previous research has shown that increases in body mass and muscle size are greater in subjects using steroids (3,22), increases in pennation might be expected with the greater muscle hypertrophy. Nonetheless, there was no significant between-group difference in muscle thickness changes in the present study. Thus, although increases in pennation might accompany increases in muscle size, other factors must have influenced pennation changes here.

One such factor might be the retention of fluid (water/salt) within the muscle that could occur with TE use (see Giorgi et al. (12)). Incorporation of water into the muscle would cause an enlargement of the muscle fibers. If the increases in fiber size were associated with increases in pennation, as some authors have suggested (19,20,28), then strength changes could have resulted. This would in turn allow greater loads to be lifted and possibly provide a greater stimulus for muscle growth. Thus, architectural changes may have preceded strength gains.

Alternatively, the greater pennation in TE subjects may have been an adaptation to greater loads lifted in training. Training logs showed that TE subjects increased their training weights faster than nonTE subjects did. Indeed, TE subjects had increased their bench press 1-RM by 13.9 kg after 6 wk, whereas nonTE subjects had only increased 3.8 kg. Although hypertrophy in other muscles (e.g., the pectoral muscle group) may have influenced strength changes, adaptations in the nervous system, enhanced recovery from training, or some other rapid adaptation may have resulted in the greater loads being lifted. Muscle architecture may have then changed in response to the higher training loads. Nonetheless, it is unclear from the present data in what order changes in muscle thickness, pennation, and strength occurred.

It appears from our results that increases in strength and pennation, and possibly decreases in fascicle length, are related to TE use (or the greater training loads used by subjects administered TE). However, there was a statistically significant difference ($P < 0.05$) between the groups in bench press strength and a marked (although nonsignificant, $P < 0.07$) difference in pennation before the study. Thus, the greater changes in strength and muscle architecture of TE subjects may have been somewhat related to their pretesting training status. Although data from Giorgi et al. (12) showed no difference in the groups in strength, muscle size, body height, and weight before the study, the nonTE subjects used for the present analysis probably represented the stronger subjects in the group. Nonetheless, strength values reported here are not likely to represent the upper limits of human strength, so changes in strength should still have been possible in both groups. It is unclear what the upper limits of architectural changes are. Interestingly, however, the stronger nonTE group also had larger pennation and greater triceps thickness (nonsignificant), which further suggests there is a relationship between strength and muscle architecture.

In summary, supraphysiologic doses of TE, when combined with high-intensity weight training for 12 wk, did not result in greater increases in triceps muscle thick-
ness than training alone. However, muscle pennation increased significantly compared with control subjects. Our estimates of fascicle length also suggested that TE administration was associated with no change, or a slight decrease, in fascicle length, whereas subjects who did not use TE may have had a slight increase in their fascicle lengths. Architectural differences between the groups may help explain their strength differences after training because muscles that have larger pennation and shorter fibers are commonly associated with high-force production. Therefore, in addition to increases in muscle size shown in other studies, some of the increase in strength associated with steroid use may be a result of architecture changes. The results of the present study, however, do not indicate whether architecture changes result from, or are the cause of, greater strength increases in TE subjects. Research investigating the mechanisms of architectural changes, especially with large subject numbers where type II error is reduced, is clearly warranted.

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